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Editorial: New challenges in space plasma physics: Open questions and future mission concepts

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Editorial on the Research Topic
New challenges in space plasma physics: Open questions and future mission concepts

For over half a century, scientific space missions have provided the experimental underpinning for advances in space plasma physics. *In-situ* and remote observations have revealed an incredible variety of processes throughout the heliosphere, including the solar corona, solar wind, and planetary magnetospheres. Fundamental plasma phenomena such as turbulence, instabilities, particle acceleration, magnetic reconnection, waves, shocks, and dissipation have been widely studied but remain to be understood in depth. Each new space mission so far has driven forward our understanding of space plasmas, but has also given rise to many new questions about our solar system. This Research Topic collects novel ideas and recent results suggesting the need for innovative space measurements, new analysis methods, and pioneering instrumentation. These are presented in 12 articles demonstrating the current and future open challenges in space plasma physics, and the proposed approaches to address them.

Verscharen et al. present "The Plasma Universe" as a common and coherent science theme that transcends traditional boundaries between research communities. In their article, a group of lead authors from white papers that were submitted to the ESA Voyage 2050 process[1] give a synopsis of fundamental physics questions and processes that are linked by this common plasma science theme. The theme combines science areas that rely on remote-sensing plasma observations and *in-situ* plasma measurements stretching from UV and X-ray astronomy over solar physics, heliospheric physics, and magnetospheric physics to cometary physics.

A number of contributions to our Research Topic highlight the growing need for multi-spacecraft missions to unveil critical multi-scale phenomena in space plasma. The research

1 https://www.cosmos.esa.int/web/voyage-2050.

article by Broeren et al. proposes improved methods to reconstruct the magnetic field based on measurements by multi-point, multi-scale spacecraft observatories. By applying their reconstruction methods to test cases and simulation outputs, the authors lay important groundwork for upcoming missions like HelioSwarm or planned missions like Plasma Observatory. These missions will go beyond the tetrahedral formations of more traditional constellations to explore plasma turbulence and structures in unprecedented detail. Maruca et al. discuss the need to go beyond the number of spacecraft in currently operating and upcoming missions to fully "image" the three-dimensional structure of the interplanetary magnetic field. Their investigation suggests that a baseline design of 24 spacecraft, combined with field reconstruction techniques, could study the mesoscale magnetic structure ($\sim 10^2$ to 10^6 km) to distinguish different models of the interplanetary fluctuations and their effect on the heliosphere. They also propose the use of CubeSat designs to comply with the budget constraints of typical mission classes. Malaspina et al. envision a 34-spacecraft magnetospheric mission that uses microsatellites and small satellites. As shown in **Figure 1**, these spacecraft would carry instrumentation for radio tomography of the equatorial plasma density, combined with *in-situ* measurements of the total plasma density and extreme ultraviolet imaging of the meridional ion density and flows. With the additional *in-situ* measurements of fields and the cold and energetic particle distribution functions, the proposed mission will help us understand the processes that govern mass and energy flow through the terrestrial magnetosphere.

In the last decades, spacecraft capable of joint *in-situ* and remote observation have gained popularity due to their cross-cutting capabilities. Inspired by the recent joint observations of Solar Orbiter, Parker Solar Probe, and BepiColombo in the inner heliospehre, the perspective article by Telloni discusses a two-satellite mission crafted to maximize orbital configurations such as conjunctions, quadratures, and alignments. Combined *in-situ* and remote-sensing payload on board such a mission will enable an in-depth investigation of the heliospheric structure and of its solar and coronal drivers. Similarly, building on STEREO and Lagrange/Vigil concepts, Bemporad proposes two identical spacecraft at the Sun-Earth Lagrange points L4 and L5. Equipped with *in-situ* and remote-sensing instrumentation, this mission will enable observations of solar magnetic field evolution, from the solar interior (stereoscopic helioseismology) to the photosphere and corona (spectro-polarimetry), and into the solar wind (*in situ*). The pair of spacecraft will also serve as monitors for the Sun-Earth connection.

In order to investigate the dynamics of heliospheric magnetic and plasma structures, Borovsky and Raines present a concept for a single spacecraft mission at 1 au, equipped with high-resolution/low-noise particle and composition measurements. The fine details of the particle distributions will help to effectively distinguish the *in-situ* or coronal origin of structures such as current sheets, containing crucial information about the radial evolution of the solar wind. A key part of understanding our heliosphere is determining the conversion of energy between its different forms, including how particles are energized by electromagnetic fields, e.g., through waves, turbulence, shocks, and magnetic reconnection. Howes et al. propose new onboard field-particle correlator instrumentation, designed to study these processes with greater capability than currently possible, that could be employed on a future kinetic plasma physics mission. This method will correlate particle detections with the observations of electromagnetic fields to measure, onboard the spacecraft, energization at multiple energies simultaneously and with much higher time resolution than ever before. It will allow downlink of high-resolution data on particle energization over long periods of a mission and enable event-based triggering. These approaches will further our understanding of energization in a variety of space plasma processes. Our Research Topic also describes novel analysis methods for space plasma data. The Methods Article by Bakrania et al. explores the use of machine-learning (clustering) techniques to classify space plasma regimes. Applied to electron distribution functions observed by the Cluster mission, the method clearly identifies eight distinct plasma regions in the Earth's magnetotail. Automated classification methods are a useful and promising tool to analyse large amounts of plasma data. In the future, methods like this may even be used onboard spacecraft to reduce the dimensionality of datasets and thus the required telemetry.

The difficulty of obtaining accurate three-dimensional electric field measurements is an important limitation of experimental space physics. For instance, in their Research Article, Wilson et al. discuss specific features of high-frequency electric field fluctuations at collisionless shocks. In particular, they show observations and numerical simulations that routinely provide contradicting results. Data show consistently large-amplitude electrostatic fluctuations, while simulations produce quasi-static fields. The authors suggest that both measurements and simulations have known limitations that may explain this discrepancy, and that improvements of both are needed in order to understand the physics of collisionless shocks. In their Methods Article, Lejosne et al. address the lack of accurate electric field measurements by proposing a novel design for an instrument specifically aimed at overcoming the known limitations. Based on detectors mounted on two orthogonal rotating plates, the new concept promises continuous high-accuracy three-dimensional electric and magnetic fields measurements, at affordable price and mass.

Finally, Borovski et al. address the need for observations of the magnetic connectivity of the equatorial magnetospheric regions with the auroral arcs. This knowledge is necessary to improve our understanding of the processes leading to the aurora. This Methods Article proposes an innovative mission concept aimed at visually pinpointing the connectivity. To achieve this goal, a spacecraft located in the equatorial magnetosphere will emit a beam of energetic electrons that, if magnetic connectivity exists, will travel along the field lines and appear as a bright spot in the polar ionosphere and upper atmosphere. A ground-based optical sensor will then image and localize the bright point, allowing a reconstruction of the connecting magnetic field line.

Our Research Topic highlights that, while awaiting new insights from recently launched spacecraft, the space plasma physics community actively proposes innovative concepts for future space missions. These creative ideas, which grow in response to theoretical and numerical advances and in light of the most recent observations, have the potential to transform our understanding of our cosmic neighbourhood and of fundamental plasma physics across our Universe.

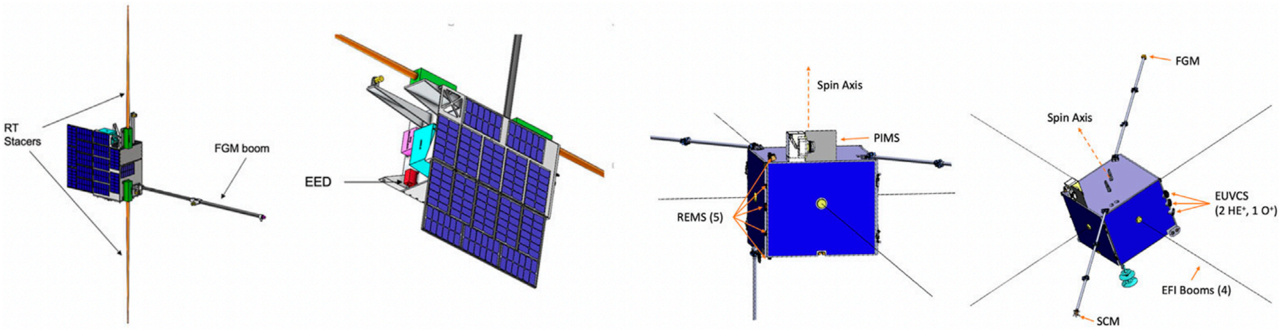

FIGURE 1
Rendering of the microsatellites equipped for radio tomography (left) and of the small satellites carrying plasma instrumentation (right). From Malaspina et al.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

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